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CHARACTERISTICS AND IMPLICATIONS OF FORECASTING ERRORS IN THE SELECTION OF R&D PROJECTS

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Characteristics and Implications of Forecasting Errors in the Selection of R&D Projects

by

Dennis L. Meadows* and Donald G. Marquis‡

Abstract

To understand the forecasting errors which must be accommodated by formal project selection models, this study investigates the relation between initial forecasts and actual outcomes in industrial product development programs. The following conclusions are based on data from 144 projects in five commercial laboratories and from computer simulations with one model of a typical development project effort.

1. The most accurate initial forecasts of project cost explain only 25 percent of the variance in actual costs. Initial estimates of probability of technical or commercial success do not usefully distinguish among projects which have different degrees of success.

2. Unsuccessful projects cost more and incur greater cost overruns on the average than do projects resulting in commercially successful products.

3. The average magnitude of cost overruns and the rate of commercial success depend in part on the functional source of the project.

4. Errors in the forecasts currently employed to select projects lead to the expenditure of more than 50 percent of the firm's development budget on technically or commercially unsuccessful projects.

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INTRODUCTION

Management's typical reaction to any proposal for a formal technological forecasting system is that the accuracy of the forecasts does not justify the cost of the system. Forecasts are inaccurate. There is little quantitative research into forecasting errors, but the few studies which have been conducted, together with a great deal of managerial experience, suggest that errors are often large. Occasionally they are catastrophic. Proponents of integrated long range technological forecasting systems cannot deny this. They can only suggest that systematic consideration of alternatives, automated handling of the vast quantities of relevant data, and comprehensive consideration of important interrelationships together offer an improvement over management's more intuitive and ad hoc approach to forecasting and planning. Such reasoning has obvious merit, but it will lack real imperative until it is accompanied by a more systematic investigation of the errors actually inherent in forecasts and of their implications for the forecasting techniques currently proposed.

The infrequent use of quantitative procedures for forecasting the value of alternative development projects illustrates this point. Formal project selection models were the first technological forecasting procedures to receive wide attention in the management science literature. A 1964 survey of project selection techniques discovered over eighty different proposed forecasting methods (Baker & Pound, 1964). The research revealed, however, that there was little implementation of any technique, primarily because none of the procedures satisfactorily treated the problem of forecast accuracy. Other evidence supports this conclusion (Kiefer, 1965).

More recent proposals for project selection formulas and for other technological forecasting techniques still have not considered the effects of the errors in the forecasts upon which they are based. A few studies have explicitly treated the problem of forecasting accuracy (Marshall & Mecklin, 1962; Peck & Scherer, 1962). They have, however, compiled only post-mortems by calculating differences between initial estimates and final outcomes. Implicit in such "before-after" research is the assumption that forecasts and outcomes do not interact in the process of technological development and transfer. The following is a more realistic representation.

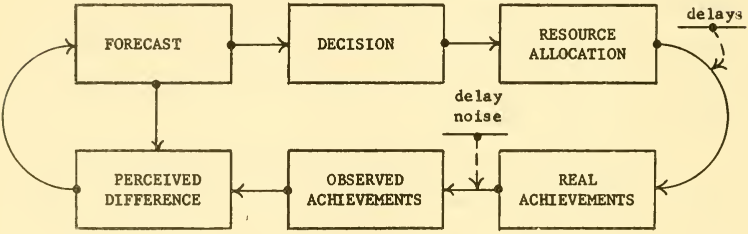

Figure 1 Decision Feedback Loop

R&D management is a dynamic process, adjusting more or less continuously to differences between what was forecast and what has apparently been achieved through the efforts of the technical staff. Decisions based on the forecasts lead to the allocation of the laboratory's resources among alternative projects. After delays inherent in the development process, this expenditure results in technical achievements. Management attempts to monitor this progress, but there are delays, noise, and often deliberate bias in both the formal and the informal communication channels of the laboratory. These factors together with initial errors in the forecasts lead to differences between management's observations and its expectations. Those differences typically lead to revised forecasts and new decisions designed to decrease the difference between perceived and forecast or desired results. Most research managers have personally witnessed this interaction between forecast and error in some project where the expected and actual cost leapfrogged each other upwards while the project's technical solution appeared always just around the corner. Obviously a before-after analysis of forecasting error does not fully characterize the errors in such a system as that illustrated above.

The continuous sequence of forecast-decision-results-errors-forecast constitutes a feedback loop, a fundamental structure inherent in the control of all physical and social systems. It is through a plexus of feedback loop structures like that in Figure 1 that forecasting techniques and their associated errors affect the performance of the firm. If we are to understand the implications of errors, they must be viewed in the context of this feedback loop structure.

Several members of the M.I.T. Research Program on the Management of Science and Technology have begun to study the characteristics and the dynamic implications of errors in the forecasts used to select among alternative development projects. I will present two aspects of that work: data on the errors which actually occur in industrial-development-oriented forecasts and results from computer simulations which trace the effects of such forecasting errors as they are propagated through the decision loop networks of the laboratory.

The specific characteristics of laboratory decision loops will vary from one firm to another, but the decision feedback loop structure underlying industrial development activity is quite general. Individual laboratory differences can easily be accommodated by statistical and simulation techniques. It is thus already possible to generalize some results of the research, and I will point out several significant conclusions. I must emphasize, however, that the real importance lies with this approach to forecasting. Thus I will stress the procedures as much as the conclusions which have so far resulted from the work. Before the potential of technological forecasting systems can be fully realized, each firm must study the process by which it plans and allocates its own resources in the development of new technology.

ACTUAL ERROR CHARACTERISTICS

The before-after approach to estimate error does not completely assess the characteristics of errors in a firm's forecasting procedures. It does, however, indicate the magnitude of the errors which forecasting procedures must accommodate. If there are sufficient data it may also reveal statistical relations between error magnitude and characteristics of the firm's organization and technology. Both of these are useful inputs to any dynamic model of error and project performance. Thus we have included this approach as the initial phase in our study. We have studied four firms in detail. Their forecasting performance will be analyzed here. Data from a fifth firm, studied by Mansfield and Brandenburg (1966) will be included to check the generality of our findings.

Data Sources

Three of the laboratories are in chemical companies engaged primarily in the development, production and sale of industrial intermediates. Two of the chemical firms, A and B, have between $100 and $300 million annual sales. The third is one of the largest firms in the nation. The fourth laboratory, called here the Electronics Laboratory, is maintained by an instrumentation company to engage in work of interest to NASA and the Department of Defense. The fifth set of project data comes from the Mansfield study of the central research unit in a prominent equipment manufacturer.

Data from each of the five laboratories were obtained from three sources. The initial estimates of project cost, probability of technical success, and probability of commercial success, when available, were obtained from project evaluation forms completed at the time each project was first approved for funding. Accounting records supplied the actual costs, and the leader of each project indicated whether the project had eventually been technically and/or commercially successful.

Data were obtained on 144 completed projects, which were divided into four mutually exclusive categories according to their outcomes.

Miscellaneous failure: The project was closed out because of manpower shortages, changes in the market objectives of the firm, or other non-technical reasons. The project did not result in a product.

Technical failure: The project was closed out when unforeseen technical difficulties prevented the development program from producing the desired product.

Commercial failure: The project did produce the product initially desired but the product was not sold.

Commercial success: The project was technically successful, and the product did produce sales income for the firm.

With the exception of Chemical Laboratory B, no attempt was made to rank projects on the basis of their technical or commercial performance. The definitions above do not apply to the projects in Chemical Laboratory C where only the estimated and actual costs for one year's development on each project were available.

The data from each laboratory were analyzed to determine the magnitude of the forecasting errors associated with each project and to discover significant relations between those errors and other attributes of the laboratory. The conclusions from this work are listed below and then followed by a detailed presentation of the data and the analyses which lead to them.

Conclusions

(1) There is a very low correlation between the values of actual and estimated cost, probability of technical success and probability of commercial success employed in selecting development projects.

(2) There is a pronounced tendency for technically and commercially unsuccessful projects as a group to incur greater cost overruns

than commercially successful projects.

(3) The average magnitude of cost overruns and the rate of commercial success may differ depending upon the sources of the project idea.

(4) Technically and commercially unsuccessful projects cost more on the average than commercially successful projects.

(5) Forecasting error typically leads management to expend more than 50 percent of a firm's development resources on projects which do not produce commercially successful products.

(6) Forecasting errors are influenced by the laboratory's organizational form.

Discussion

(1) There is a very low correlation between the values of actual and estimated cost, probability of technical success and probability of commercial success employed in selecting development projects.

Cost Estimates

In Chemistry Laboratories A and B, the cost of successfully meeting the technical requirements of a project is predicted before deciding whether it should be funded. The actual costs of projects which were technically successful can thus be compared with the initial estimates to obtain one measure of the error in those estimates. Figures 2 and 3 compare initial estimates with actual costs for each of the two organizations. The actual costs are generally found to differ substantially

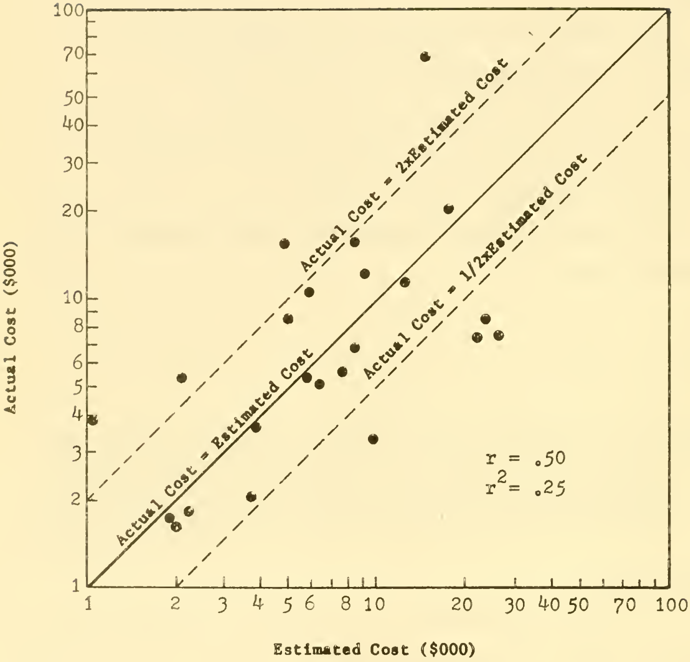

Figure 2 Estimated vs. Actual Costs for 23 Technically Successful Projects - Chemical Laboratory A

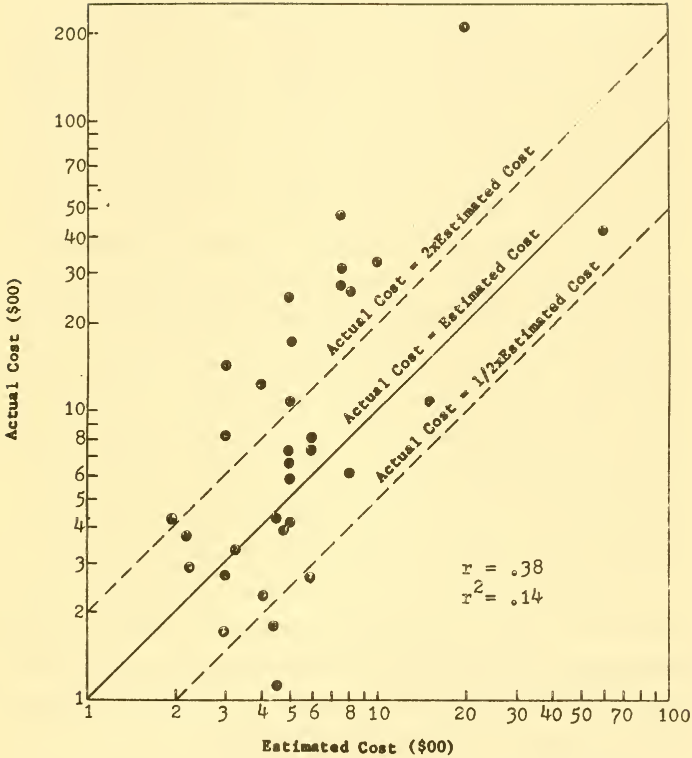

Figure 3 Estimated vs. Actual Costs for 33 Technically Successful Projects - Chemical Laboratory B

from those initially forecast. Where there are deviations of this type, it has been suggested that a linear formula:

Actual cost = a + (b) (estimated cost)

be employed to modify the initial estimates, correcting for the errors inherent in them (Fisher 1963). It is easy to determine statistically the "best" linear formula for any given set of historical data, but many factors not explicitly considered can limit the predictive ability of such an equation by causing some deviation of the actual costs from the modified estimates. The correlation coefficient (r) measures this deviation. The quantity r^2 indicates the percent of the variance in actual costs which is explained by the modified estimates. If r (consequently r^2) is low, the estimates will be of little use in predicting actual costs. The correlation coefficient for each set of projects is given on the corresponding figure. The most accurate estimates, those in Chemical Laboratory A, explain only 25 percent of the variance in the actual project costs even when these estimates are modified with the best linear correction formula for that particular set of data.

In Chemistry Laboratory C project costs are predicted for only one year at a time. The uncertainty in annual cost estimates should be substantially less than that in the initial estimates of total project costs. The estimates were found, however, to account for no more than 57 to 74 percent of the variance in actual costs.

Historical data on cost forecasting accuracy may also be expressed in the form of cumulative frequency distributions. Figures 4 and 5 present the cumulative frequency curves of cost overruns among the projects studied in Chemical Laboratory A and B respectively. In Laboratory B,

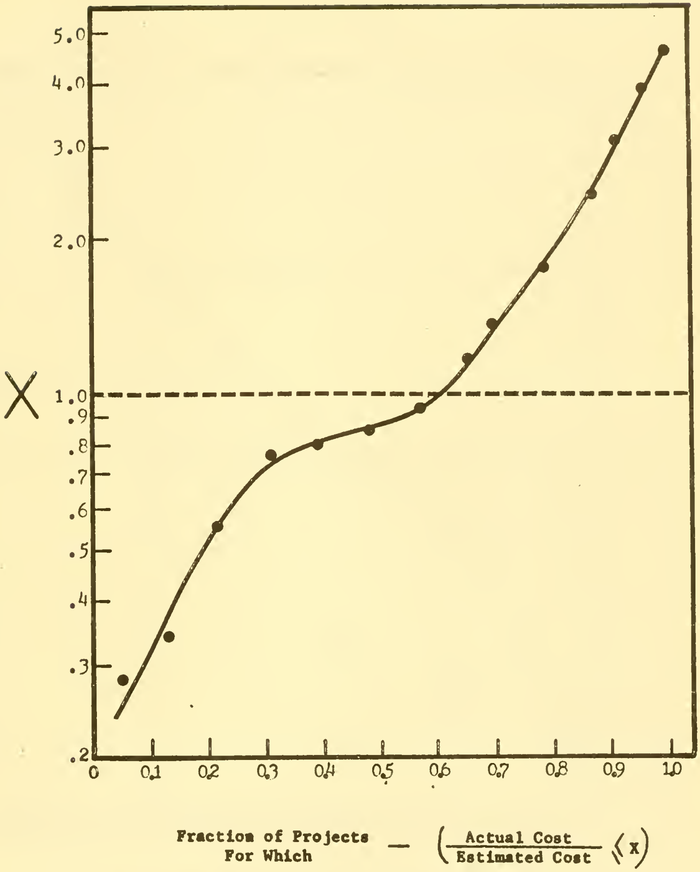

Figure 4 Cumulative Distribution of Cost Overruns for 23 Technically Successful Projects - Chemical Lab A

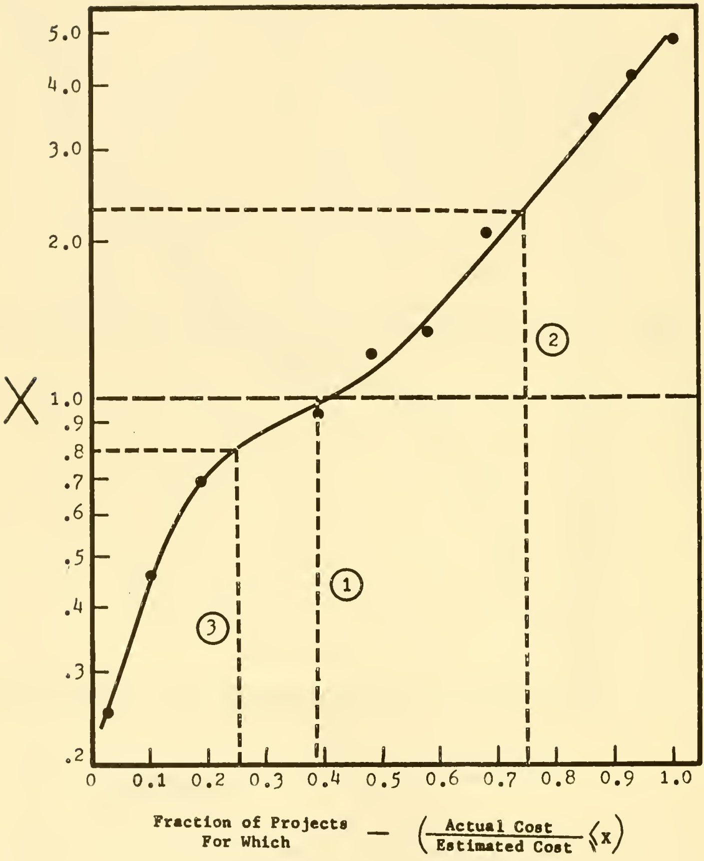

Figure 5 Cumulative Distribution of Cost Overruns for 33 Technically Successful Projects - Chemical Lab B

as indicated by dotted line "1", 38 percent of the projects were completed without incurring cost overruns. For those projects the ratio, actual cost/estimated cost, was less than or equal to 1.0. Similarly, 75 percent of the same projects were completed at less than or equal to 2.4 times the initially forecast development cost (dotted line 2). This representation of historical errors has particular value in evaluating the utility of forecasting models. Its use in this role will be discussed later.

Probability Estimates

The staffs of Chemical Laboratory A and the Equipment Laboratory estimate the probability of technical success and the probability of commercial success of each development project before deciding whether or not it should be funded. The estimated values are employed by management as if they characterized a binomial process. For example, of all the projects which receive the initial estimate PTS = 0.80, 80 percent are expected to be technically successful.

Probability estimate errors are more difficult to measure than cost estimate errors. A numerical overrun ratio can be employed to indicate the error in an estimated cost figure. There is no equivalent measure of probability estimate error. When a coin lands with one side up on eight of ten toses, it does not necessarily disprove the initial estimate that the probability of that side landing up is 0.50. Similarly, a deviation between the fraction of projects which actually succeed and the probability of technical success initially assigned a set of projects does not necessarily prove the initial estimate to have been in error. A deviation of the fraction actually successful from that expected on the basis of the initial forecast is particularly likely to occur when there are only a few projects in the group. Thus only statistical measures of probability estimate error are useful.

To measure the accuracy of the probability of technical success estimates in Chemistry Laboratory A, all projects were divided into classes according to the probability of technical success values initially assigned (horizontal axis of Figure 6). The fraction of each group which actually succeeded was determined from the data, and these fractions are indicated by the vertical white bars. Finally, that fraction actually technically successful was used to calculate limiting values of the true probability of success which the staff attempted initially to forecast. From the fraction actually successful in each set of projects, an interval was found which has a 50 percent probability of including the true but unknown, probability of technical success. These 50 percent confidence intervals are shown in Figure 6 as shaded bands. Although the procedure is complicated, it is not difficult to interpret the results. If the estimates are accurate, about half of the shaded bands should cross the line indicating the expected fraction successful.

The measurement of probability of commercial success differs from the above in only one respect. Each estimate of probability of commercial success was based on the assumption that the project would be technically successful; i.e., that it would result in a marketable product. Thus only the 23 technically successful projects are included in the analysis shown in Figure 7. Missing data on three projects permit the

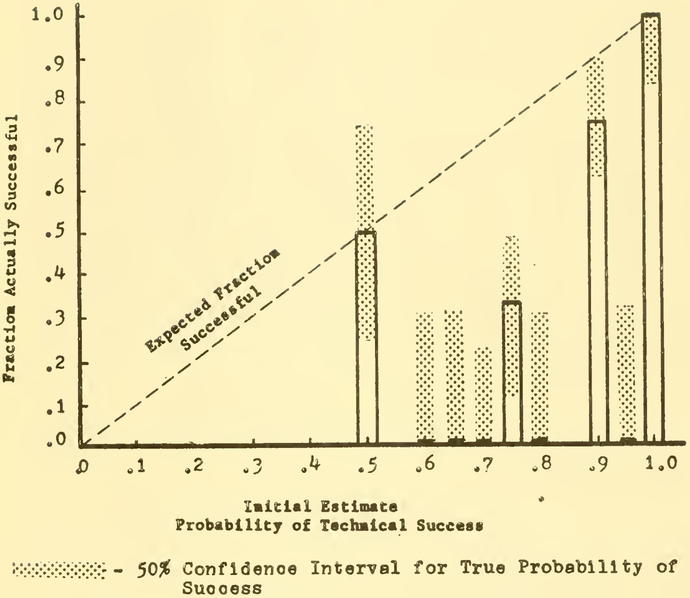

Figure 6 Accuracy of Estimated Probability of Technical Success for 30 Projects, Chemical Laboratory A

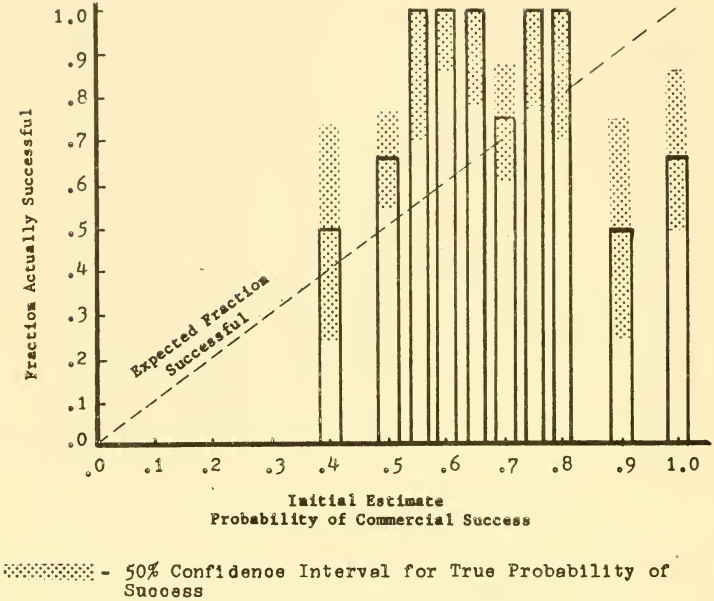

Figure 7 Accuracy of Estimated Probability of Commercial Success for 20 Projects, Chemical Laboratory A

accuracy to be measured for only 20 projects. It is apparent that neither the forecast probability of technical success nor probability of commercial success distinguish usefully between the more and the less successful projects. The results also tend to confirm laboratory managers' belief that market estimates are less reliable than technical estimates (Seiler, 1965, p. 177).

Mansfield and Brandenburg (1966) assigned a different meaning to the Equipment Laboratory probability of technical success estimates. Thus their analysis of estimate error differs from that described above. Nevertheless, they too conclude that "although there is a direct relationship between the estimated probability of success and the outcome of a project, it is too weak to permit very accurate predictions"(1966, p. 462).

(2) <u>There is a pronounced tendency for technically and commercially unsuccessful projects as a group to incur greater cost overruns than commercially successful projects</u>.

When projects are grouped according to their outcomes, the ratio of total actual to total estimated costs for the unsuccessful projects of each laboratory is found to be greater than for the corresponding group of successful projects. This finding applies to the three laboratories in which the necessary data were available, and it appears to be independent of the average size of the projects undertaken by the laboratories. It will be explained later in terms of the decision structure underlying the allocation of resources to development projects. Table 1 shows the average cost overrun for each category of project in the three laboratories.

TABLE 1

Average Cost Overrun by Project Outcome

	Laboratory		
Project Outcome	Chemical Lab A	Chemical Lab B	Equipment Lab
Miscellaneous failure	2.55*	3.84*	0.96
Technical failure			1.25
Commercial failure	1.28	4.25	0.96*
Commercial success	0.94	1.27	

*Two categories were combined in collecting the data.

(3) The average magnitude of cost overruns and the rate of commercial success may differ depending upon the sources of the project idea.

Cost Overrun

In Chemistry Laboratory B the source of the project idea was recorded. It is thus possible to determine the average cost overrun of projects initiated by the laboratory, the marketing staff, and by the customer (Table 2).

TABLE 2

Average Cost Overrun by Project Source

Chemical Laboratory B

Source of Project Idea	Average $\frac{\text{Actual Cost}}{\text{Estimated Cost}}$
Laboratory	2.20
Marketing department	2.02
Customer	1.27

The different overruns in Table 2 probably correspond to the magnitude of technological advance attempted in each group of projects. Customers would tend to request only product modifications, while laboratory personnel are inclined to suggest more difficult technical problems. The marketing staff would presumably fall between the two extremes. This interpretation is supported by a study of military development projects conducted by Marshall and Mecklin. Twenty-six programs were divided into three categories according to the magnitude of the technological advance each attempted. The cost overrun factors were 1.4 for small, 1.7 for medium, and 3.4 for large technological advances (Marshall & Mecklin, 1962, p.472).

Rate of Success

Projects in Chemistry Laboratory B which were initiated at the suggestion of customers have a much greater probability of commercial success than projects originating in either the marketing department or the laboratory. Table 3 gives the percent of each project class which resulted in no sales, small, medium, or large sales. The expenditure on projects from each source is also included in the table. Taken together, Tables 2 and 3 suggest that the magnitude of uncertainty associated with a development project may be related to the project source.

TABLE 3

Commercial Outcome by Project Source

Chemical Laboratory B

Incremental Sales	Source of Project Idea		
	Laboratory	Marketing	Customer
None	66%	58%	33%
Small	17	14	33
Medium	17	14	13
Large	0	14	21
	100%	100%	100%
Percent of total budget expended	40	40	20

(4) <u>Technically and commercially unsuccessful projects cost more on the average than commercially successful projects</u>.

Data presented above indicated that unsuccessful projects tend to incur greater cost overruns. Table 4 illustrates the tendency of unsuccessful projects to cost more in absolute terms as well.

TABLE 4

Average Project Cost by Project Outcome

Project Outcome	Average Project Cost*			
	Chem Lab A	Chem Lab B	Equip. Lab	Elec. Lab
Miscell. failure	3.21‡	2.51‡	0.60	0.67
Technical failure			1.16	2.28
Commercial failure	2.21	2.36	1.00‡	1.05
Commercial success	1.00	1.00		1.00

* Costs are expressed as a multiple of the average project cost for commercially successful projects in the respective laboratory.

‡ Two categories were combined in collecting the project data.

(5) Forecasting errors lead management to expend more than 50 percent of the firm's development resources on projects which do not produce commercially successful products.

Projects which are closed out before they result in a product may contribute some new knowledge to future projects, but they produce no direct sales revenue or profit for the firm. The errors in current forecasts result in most of the firm's development expenses being invested in this type of project. Table 5 shows the allocation of money among the four project clases actually found in the study.

TABLE 5

Laboratory Investment in Unsuccessful Projects

Project Outcome	Investment as a % of Total Cost			
	Chem Lab A	Chem Lab B	Equip. Lab	Elec. Lab
Miscell. failure	45%*	18%*	27%	10%
Technical failure			20	25
Commercial failure	37	51	51 ‡	18
Commercial success	18	31		47
	100 %	100 %	98%	100 %

* Project leaders responded to the question, "Did the project achieve its technical objectives?" Thus no distinction was made between technical and miscellaneous failures.

‡ Mansfield and Brandenburg did not obtain information on the commercial outcome of the projects in his study. Thus it is impossible to distinguish between those projects which were commercially successful and those which succeeded only technically. Rounding errors prevent percent total actual cost from equaling 100 percent.

(6) <u>Forecasting errors are influenced by the laboratory's organizational form</u>.

It was suggested above without any objective support that forecasting errors and the decision structure of the laboratory interact throughout the conduct of a development project. The conclusion was initially derived from qualitative consideration of the way in which development work is actually carried out, but it is supported by the research results available on forecasting errors.

Chemical Laboratory C underwent a thorough reorganization during the course of our study. Initially the laboratory was organized along scientific disciplines. All work was channeled through a steering committee composed of top laboratory and corporate personnel. The reorganization placed control of most development decisions with product-oriented business teams composed of technical, production and marketing representatives. Data are available on the forecasting accuracy of the laboratory staff two years before and two years after the reorganization. Although the data represent cost forecasts by the same laboratory personnel for roughly comparable projects, there is a significant improvement in the accuracy of forecasts after the reorganization.

Research by Rubin (1967) on government sponsored development projects also indicates the relation between forecasting accuracy and laboratory organization. The cost and schedule overruns in 37 development projects averaging four million dollars in total cost were measured. Work on 20 of the projects was controlled with PERT procedures; 17 laboratories used some other procedure. Seventy-one percent of the laboratories not using PERT incurred overruns, only 40 percent of the laboratories using PERT incurred similar overruns.

Generality of the Errors

We are accumulating data from other laboratories, but those included in the sample above are considered technical leaders by their competitors. Each company is profitable and growing. One cannot dismiss the seemingly poor estimating performance as the result of inept technical staff or poor management. Neither can the errors be attributed to the relatively poor predictability of the particular parameters studied. Probability of technical success and project cost are the two parameters which laboratory managers feel they can forecast most accurately (Seiler, 1965, p.177). Thus it is expected that similar errors will be found to characterize most of industry's short term technological forecasts. The data above are taken from four different industries and they represent projects which differ greatly both in size and in the amount of technological advance attempted. It appears likely therefore that most firms are confronted with similar errors in the technological forecasts upon which their development decisions must be based.

IMPLICATIONS OF FORECASTING ERRORS

Information on the characteristics of errors in short run forecasts is useful only to the extent that its effect on the performance of the firm and, indirectly, on the technological forecasting procedures can be determined. The implications of any errors will depend upon the way in which the forecasts are employed. The project cost and product sales forecasts typically are used in two ways: (1) to select among alternative projects on the basis of their forecast profit, and (2) to schedule the effort of the laboratory personnel, i.e. to determine how many projects may be undertaken and to assign the available personnel among them. It is quite easy to determine the effects of errors when forecasts are used in the first role. To measure the impact of inaccuracy on scheduling decisions, however, we must return to the notion of the decision feedback loop structure underlying laboratory management.

Forecasts for Selecting Projects

In forecasting profitability, the effects of errors are quite straightforward. Simple arithmetic will reveal for those projects undertaken the decrease in profits which stems from development cost overruns, over-optimistic sales forecasts, or projects terminated before they produce a marketable product. Elimination of the errors in predicting technical and commercial success would permit the firm to cut its development expenditures by 50 percent or more without any decrease in the generation of new products.

It is important to distinguish in such analyses between contract and market-oriented development. In fixed price or incentive contract research with no production follow ons, sales forecasts are not relevant. Cost estimate errors will, however, be an important determinant of the firm's profit. Cost forecasts in error by as much as 400 percent have been found; these would have tremendous impact on the contract-oriented laboratory.

In commercial development programs, the situation is reversed. Costing errors are relatively unimportant. Development costs are typically a small percentage of the profits from a successful product, and cost overruns of even 100 or 200 percent will not generally be important in comparison to the profit. However, even small errors in the sales forecasts can make important differences in profit.

When using a formula or other quantitative procedure to forecast the profit of a proposed project it is important to know the confidence which may be placed in the forecast. Error research similar to that presented above, when carried out by a firm on the records of development projects it has recently completed, will permit management to calculate approximate confidence intervals for the forecasts it currently is employing. The information required for these calculations can most usefully be supplied in the form of the cumulative frequency curves.

Figures 4 and 5 give the cumulative frequency distributions of different cost forecasting errors among the projects already completed in Chemical Laboratory A and B. Similar curves could be constructed for sales estimates or any other quantitative forecasts for which the actual outcomes can be presently measured. To the extent that projects under consideration are similar to those completed by the firm, the historical cumulative frequency curves may be taken as good indications of the errors likely to be found in current forecasts. Under these circumstances it would become possible to construct history-based confidence intervals about the current forecasts.

One simple example may illustrate the use of cumulative frequency data in this way. Suppose the director of Chemical Laboratory B has been given an estimate of $10,000 for the development cost of a project currently under consideration for funding. If it were undertaken, the project would be conducted by the same personnel who were involved in the completed projects represented in Figure 5. The new product concept is also based on the same general fund of technical expertise as the completed projects. Thus the manager expects the forecast cost figure to be about as accurate as those he has received in the past.

Figure 5 shows that 25 percent of the completed projects in Chemical Laboratory B exceeded their initially estimated cost by 240 percent (dotted line 2). The manager could thus assign a probability of .25 to the chance that the new project would ultimately cost more than \$24,000. Similarly, he would assign a value of 0.38 to the probability that the new project would cost less than the \$10,000 forecast (dotted line 1), and a value of 0.25 to the probability that it would cost less than \$8,000 (dotted line 3). The chances of other errors may similarly be determined from the cumulative overrun curve.

This technique may be extended to formulas which incorporate more than one potentially inaccurate forecast. For example, the commonly used Expected Profitability Ratio:

$$\text{Expected profit ratio} = (\text{PTS})(\text{PCS})(\text{net profit})/(\text{dev. cost})$$

PCS=Probability of commercial success
PTS=Probability of technical success

may be treated in the same manner. It is only necessary that cumulative error frequency curves have been determined for each of the forecasts used in the calculation, and that the forecast and project be similar to those for which past data are available. The utility of the procedure can be determined in each laboratory only by trial. In general, however, the calculation of history-based confidence intervals will provide useful information on the implications of errors in the forecasts used for predicting the profitability of projects.

Forecasts for Scheduling Personnel

It is not as easy to determine the implications of errors inherent in the forecasts which are used to schedule the laboratory's resources, for there the feedback loop structure of decision making becomes especially important. The simple decision loop in Figure 1 may be elaborated to represent the information feedback structure underlying the scheduling of resources in development projects. Figure 9 represents a development program in which man-hours are the principal input and cost.

Personnel are initially allocated to the project on the basis of the desired completion date and the estimated total man-hour requirements of the technical task. Because the desired and the forecast completion date are initially the same, the engineers' motivation and hence their productivity are somewhat less than that obtainable under conditions of extreme schedule pressure. There will typically be more time wasted or spent on unnecessary engineering refinements than in a crash program.

The number of engineers assigned to the project, their technical competence, and their level of motivation together determine the rate of progress toward the technical objectives of the project. Technical progress is generally difficult to quantify, however, and social communication systems all have inherent delays and errors. Additional errors and bias are introduced by the attitudes and the motivations of the engineers and their immediate supervisors. The technical personnel know the current schedule and the rewards and penalties associated with positive and negative deviations from it. This information together

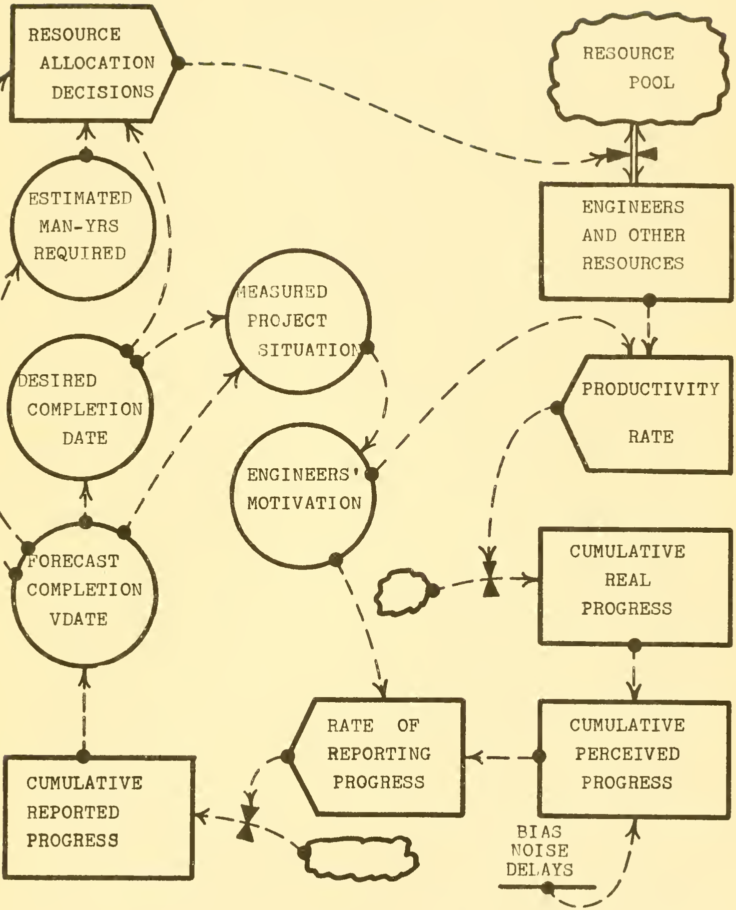

Figure 9 Feedback Loop Structure of Project Management Decisions (modified from an unpublished memo by E. B. Roberts)

with their perception of the actual progress will influence the problems and the achievements which they report to the laboratory management. Whether cumulative progress is monitor informally or through some procedure like PERT, management will generally be forced at some point during the project to revise the forecast completion date. Faced with a project slip, management may revise the desired completion date, assign more men to the project, or exert more pressure on the current engineering staff. Whatever management's course, the effects of its decisions will be propagated through the system of loops to result eventually in new inputs for further decisions.

In this context simple calculations or sensitivity analyses are no longer adequate for understanding the implications of forecasting errors. Inaccuracies may lead to many different kinds of costs depending upon the nature of the decision structure in the laboratory. Technical manpower resources are relatively fixed in the short run. Men precipitously added to one project effort must be taken from another. The program with lower priority will itself experience schedule overruns, or often be dropped altogether. Such projects appeared above in the category of Miscellaneous Failures. Table 5 indicates that the money wasted on this type of project amounted to 27 and 10 percent respectively of the total development budgets in the Equipment and the Electronics Laboratories.

Another cost stems from the time inevitably lost whenever men are transferred from one project to another. The project effort is disrupted while the new personnel become familiar with the work and are assimilated into the working groups. Also, there may be penalties associated with schedule overruns.

The magnitude of all these costs will depend upon the size and direction of the initial error, the speed at which it is detected, the efficiency with which resources are transferred between projects, and the implications of schedule overruns. The specific values of these and other parameters in the laboratory's underlying decision structure may change from one laboratory to another, but the structure itself is a general representation of all project-organized development programs.

It is actually possible to fit the parameters of such a model to a particular laboratory. Management science and organization psychology, the experience of corporate and laboratory administrators, and empirical research similar to that discussed above all can provide information on the elements and the relationships which comprise the important feedback loops in any particular laboratory. In practice, of course, the description will be much more detailed than that in Figure 9. We have found that laboratory simulation models must contain about thirty elements before they begin to exhibit the behavior modes characteristic of real organizations. Some of the models which have been used to explore laboratory performance are an order of magnitude more complex than that.

While it is possible for managers to describe accurately the decision feedback structure which determines the performance of their laboratories, the complexity of any useful model makes it impossible to intuitively predict the costs which will result from different forecasting errors. Thus the laboratory description must be converted into a set of equations which can be employed in computer simulation experiments. Industrial Dynamics is a technique to identify the information feedback structure which determines the performance of social or economic system and then convert it into a computer simulation model. Several references (Forrester, 1961; Roberts, 1964; Spencer, 1966) give specific instructions in the methodology of Industrial Dynamics and describe its application to industrial development programs.

An unpublished study by Roberts and Scambos illustrates the use of Industrial Dynamics in studying the implications of forecasting errors. Their study focused on the schedule slippages which result from errors in the initial forecast of effort required; i.e. development cost. Their simulation model elaborated on the basic feedback structure in Figure 9 by incorporating several important features.

1) The magnitude of the error, its direction, and the rate at which it became apparent to management were varied in the simulations.

2) Two engineering groups were involved in the conduct of the project. Their activities were interdependent. Whenever one group slipped too far behind the other, the second group was held up in its work as technical information and hardware necessary for its work were not available from the laggard group. The productivity of each group was influenced by its perceptions of the other's progress. Although management is usually content merely to meet minimum standards, engineers generally prefer to refine the product technically. Thus each group in the simulation model paces itself to finish just behind the other. That goal prevents it from delaying the project, yet it provides the most time for technical refinements.

3) Technical competence was held constant during the course of the project. More detailed models have included the dependence of competence upon management's hiring, firing, and training policies and

upon the past work experience of the laboratory staff.

Two results of the model simulations are important here. First, it was more costly in terms of schedule slippages to underestimate than to overestimate the required effort. Underestimating caused large schedule slippages. The minimum time required to complete the simulated project was 36 months. Estimates only 50 percent in error increased that time to 58 months. Figure 10 indicates the slippage resulting from different forecasting errors. Overruns increased expotentially with the magnitude of the forecasting error.

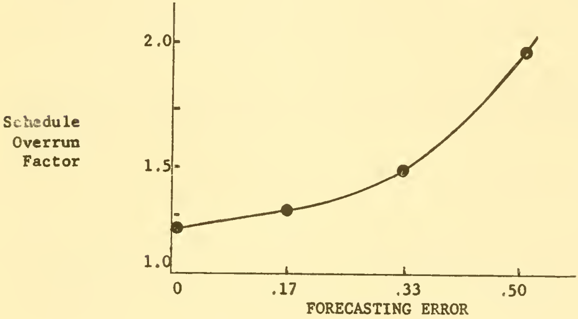

Figure 10. Schedule Overrun Associated with Different Forecasting Errors

CONCLUSION

Errors in the forecasts used to select development projects are large and costly in terms of wasted resources and schedule overruns. Inaccuracy can not be much improved through simple correction equations. Instead management must quantify the error and its implications through research. Only then will it be possible to design optimal forecasting and project selection procedures. While the results of present research must be confirmed and extended, there is no longer any doubt that both simulation and historical analysis can provide useful insights into the forecasting performance of industrial laboratories.

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